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Original Article

Ackermann's Formula in Global Fuzzy Synergetic Power System Stabilizer

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Abstract *- Small-signal stability remains a crucial research area in power engineering. Oscillations arise in synchronous machines when small disturbances create an imbalance between mechanical and electrical torques. If adequate damping is not provided, these oscillations degrade the quality, continuity, and stability of power system operation. Conventional power systems commonly employ Power System Stabilizers (PSSs) to mitigate such oscillations. This work proposes a novel global fuzzy synergetic power system stabilizer based on Ackermann's formula. The design procedure consists of three main steps. First, a synergetic control approach is applied to develop operating-point-specific models for individual power subsystems. Second, Ackermann's formula is used to compute the macro-variable gain for each subsystem within the synergetic framework. Third, a fuzzy technique is employed to integrate all subsystem models and their corresponding macro-variable gains into a global model for the synchronous machine power system. System stability is guaranteed using Lyapunov's second theorem. The effectiveness of the proposed method is evaluated through simulation studies under severe operating conditions of a single-machine power system model. Results demonstrate that the global fuzzy synergetic stabilizer provides superior damping performance compared to both the conventional PSS and the synergetic control approach.*

Keywords *- Ackermann's Formula, Global Fuzzy Synergetic Control, Power System Stabilizer (PSS), Single Machine Infinite Bus (SMIB), Lyapunov Stability.*

1. Introduction

The Power system Power systems must remain reliable and resilient under a wide range of disturbances [1]. In such systems, active power is primarily determined by the phase angle difference between the sending and receiving ends, while reactive power depends on voltage magnitudes [2]. Dynamic models represent active and reactive powers at any given time as functions of bus frequency and voltage. In a stable system, synchronous generators quickly return to their initial states after small perturbations. However, disturbances can induce oscillations, which require adequate damping to maintain system stability. Insufficient damping in complex, nonlinear power systems may result in low-frequency oscillations under unfavorable operating conditions, potentially leading to a loss of synchronism [3]. To mitigate these oscillations, synchronous machine Power System Stabilizers (PSSs) are integrated with the excitation system. These stabilizers have long been designed using conventional linear models based on a fixed operating point, typically implemented via cascade interconnected lead-lag compensators. While effective for small disturbances around a nominal operating point, these linear approaches often fail under varying load conditions or large disturbances [4, 5]. Several studies have explored methods for designing and optimizing PSSs. For example, Adaptive Stabilizers [9], Sliding Mode Control [10], Synergetic Stabilizers [11], and Adaptive Fuzzy Sliding Stabilizers [12] have been proposed to improve damping across multiple oscillation modes. Pole placement techniques [7, 8] and heuristic optimization approaches, such as genetic algorithms [14] and particle swarm optimization [15], have also been employed to tune stabilizer parameters. Neural network-based optimal PSS designs have been reported in [16], while fuzzy logic-based global models that integrate multiple linear operating-point-specific models have been explored in [17]. Despite these advances, many methods either optimize performance for a specific oscillation mode or fail to provide robust damping across varying operating conditions. To address these challenges, this study proposes a novel global fuzzy synergetic power system stabilizer. In this approach, the synergetic gain of each subsystem's macro-variable function is calculated using Ackermann's formula [18], and fuzzy logic is employed to integrate all subsystems into a global model. This methodology ensures robust damping performance across a wide range of operating points. The following sections present: (i) the synergetic control design using Ackermann's formula, (ii) the global Takagi-Sugeno fuzzy synergetic technique and associated stability considerations, and (iii) the power system model, simulation results, and comparative analysis under nominal and severe operating conditions against conventional PSS and synergetic control.

2. Power System Model

This work studies the calculation of a linearized power system model, in which an infinite bus is connected to a single synchronous machine via a double-circuit transmission line. The fourth-order classical state-space representation is given in (1).

$$\dot{x} = \begin{bmatrix} -\frac{D}{M} & -\frac{K_1}{M} & -\frac{K_2}{M} & 0 \\ \omega_0 & 0 & 0 & 0 \\ 0 & -\frac{K_4}{T'_{d0}} & -\frac{1}{T'_{d0}K_3} & \frac{1}{T'_{d0}} \\ 0 & -\frac{K_4K_5}{T_A} & -\frac{K_AK_6}{T_A} & -\frac{1}{T_A} \end{bmatrix} x + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{K_A}{T_A} \end{bmatrix} u \quad (1)$$

Where the state variables are written as follows: $x = \left[\Delta\omega(t)\ \Delta\delta(t)\ \Delta e'_q(t)\ \Delta e_{fd}(t)\right]^T$.

V : voltage of the infinite bus,
M: inertia moment coefficient
D: damping coefficient
e_{fd} : voltage of equivalent excitation,
e'_q: transient voltage component in q-axis,
$\Delta\omega$: deviation speed,
$\Delta\delta$: deviation angle,
K_A : gain voltage regulator,
T_A : constant time voltage regulator,
T'_{d0} : d-axis transient open circuit time constant,
M : coefficient of inertia moment,
D : coefficient system damping,
P, Q: real and reactive power, respectively
x_d: direct reactance,
x'_d: d-axis transient reactance,
x_q: q-axis synchronous reactance,
x_e: line reactance

Note that the calculation of the six parameter constants $K_1 - K_6$ in the linearized model of a synchronous machine is a function of real power P and reactive power Q.

Where,

$$K_1 = \frac{V^2(x_q - x'_d)\left(P/\left(P^2 + \left(Q + (V^2/x_e + x_q)\right)^2\right)\right)}{(x_e + x_q)(x_e + x'_d)} + Q + \frac{V^2}{x_e + x_q} \quad (2)$$

$$K_2 = \frac{V}{(x_e + x'_d)}\left(P^2/\sqrt{P^2 + \left(Q + \left(V^2/(x_e + x_q)\right)\right)^2}\right) \quad (3)$$

$$K_3 = \frac{(x_e + x'_d)}{(x_e + x_d)} \quad (4)$$

$$K_4 = V\frac{(x_d - x'_d)}{(x_e + x'_d)}\left(P/\sqrt{P^2 + \left(Q + (V^2/x_e + x_q)\right)^2}\right) \quad (5)$$

$$K_5 = \left(x_e \frac{V}{(x_e + x'_d)}(P/(V^2 + Qx_e))\right)\left(\left(\left(\frac{V^2x_q(x_q - x'_d)}{(x_e + x_q)}\right)\left(Q + \frac{V^2}{x_e + x_q}\right)\middle/\left(P^2 + \left(Q + \frac{V^2}{x_e + x_q}\right)^2\right)\right) - x'_d\ \right) \quad (6)$$

$$K_6 = \frac{x_e}{(x_e + x'_d)}\left(\sqrt{P^2 + \left(Q + \left(V^2/(x_e + x_q)\right)\right)^2}/(V^2 + Qx_e)\right)\left(x_e + \left(\left(\frac{V^2}{x_e + x_q}x_q\left(Q + \frac{V^2}{x_e + x_q}\right)\right)\middle/\left(P^2 + \left(Q + \frac{V^2}{x_e + x_q}\right)^2\right)\right)\right) \quad (7)$$

The parameters of the single synchronous machine infinite bus system are as follows:

$x_e = 0.4p.u$, $x_q = 1.55p.u$, $x_d = 1.6p.u$, $x'_d = 0.32p.u$, $D = 0$, $T'_{d0} = 6s$, $H = 5s$, $T_A = 0.05$, $K_A = 50$, $V = 1p.u.$

3. Synergetic Control Based on Ackermann's Formula

The synergetic technique is a state-space-based control design method for complex, interconnected nonlinear systems, grounded in the theory of combined regulators. In synergetic control, the state variables are required to evolve on an invariant manifold chosen by the designer. This ensures that the desired system performance is achieved despite disturbances and uncertainties, without the destructive chattering that is characteristic of sliding mode control. Consider a system described by:

$$\dot{x} = Ax + Bu \quad (8)$$

Where x is the vector of state variables, $A \in R^{nxn}$, $B \in R^{nxq}$ and u is the proposed synergetic input.

Begin by designing a macro variable that depends on the state variables vector.

$$\Psi = \psi(x, t) \quad (9)$$

Control will oblige the system to work on the manifold $\Psi = 0$. The designer can choose the characteristics of the macro variable based on specification control. This macro variable may be a linear simple combination of all state variables. You can repeat the procedure in an identical manner, defining as many macro variables as the approach of control. Given a standard constraint (3), the selected macro variable is chosen to adapt in a preferred manner despite the disturbances and/or uncertainties.

$$T_c\dot{\Psi} + \Psi = 0, \quad T_c > 0 \tag{10}$$

T_c: The designer's choice influences the attractor's rate of convergence, and it can be arbitrarily small when taking simply the eventual control constraint.

The macro-variable in this study is defined as:

$$\Psi = C^T x \tag{11}$$

C is the synergetic vector, for which Ackermann's method can be used to determine.

An excellent choice of macro variables allows the designer to develop an extensive number of attractive characteristics for the best synchronization, parameter insensitivity, suppression of noise, and stability. It is important to note that global stability is guaranteed by the synergetic control law on the manifold, indicating that after the manifold is attained, with large-signal variances, the system is not intended to abandon it.

The ideal dynamic properties may be provided by a proper selection of the vector C. In this paper, we show how to find the macro-variable gain vector utilizing Ackermann's formula, concerning the task of eigenvalue placement.

The eigenvalues $\lambda_1, \lambda_2, \dots, \lambda_n$ of the system (8) may be assigned utilizing Ackermann's formula.

$$C = e^T P(A) \tag{12}$$

where

$$e^T = (0, \dots, 0, 1)(B, AB, \dots, A^{n-1}B)^{-1} \tag{13}$$

$$P(\lambda) = (\lambda - \lambda_1)(\lambda - \lambda_2)\cdots(\lambda - \lambda_{n-1})(\lambda - \lambda_n) \tag{14}$$

The following is a summary of the design algorithm:

Step 1: The desired value of the synergetic approach $\lambda_1, \lambda_2, \dots, \lambda_{n-1}$ is selected.

Step 2; The macro-variable equation $\Psi = Cx = 0$ is found as: $C^T = e^T(A - \lambda_1 I)(A - \lambda_2 I)\cdots(A - \lambda_{n-1} I)$

Step 3: The synergetic control is obtained.

$$u = -(C^T B)^{-1}\left(C^T A x + \frac{1}{T_c}\Psi\right) \tag{15}$$

This control law enables satisfaction of the Constraint (10) assuming (CB) is non-singular.

4. Fuzzy Synergetic Control Design

In this technique control procedure, a Takagi-Sugeno fuzzy model is employed in order to serve as a representation of a global system model of the under nonlinear plant. A fuzzy model explained by fuzzy ''IF-THEN'' rules signifies local linear input-output relations of the nonlinear system under study. The primary characteristic of a Takagi-Sugeno fuzzy model is expressing the local dynamics of all fuzzy rules by a linear subsystem model.

Global fuzzy system model is done by fuzzy "Blending" the operating point based linear subsystem models.

The i^{th} rule of the Takagi-Sugeno fuzzy model is of the next structure:

IF z_1 is F_1^i AND … z_p is F_p^i THEN

$\dot{x} = A_i x + B_i u,$

$\Psi = {C_i}^T x, \; i = 1, 2, \dots, m$ (16)

Where

$F_j^i (j = 1, 2, \cdots, p)$: fuzzy sets,

m: number of inference rules,

x, u: state and the input vectors respectively,

A_i, B_i, C_i are respectively the matrices and synergetic vector of the i^{th} system, and $z_1, \dots, z_p$ are some of the system's measurable variables.

For example, the active and reactive powers in our work $P\ Q$.

By using a conventional fuzzy inference technique, that is, using the singleton method for fuzzifier, product fuzzy for inference, center average defuzzifier, and let $\mu_i(z)$ the normalized fuzzy membership function satisfy

$F^i = \prod_{j=1}^{p} F_j^i(z_j)$ and $\sum_{i=1}^{m} \mu_i = 1$ (17)

Where $F_j^i(z_j)$ is the grade membership z_j in the fuzzy set F^i.

The global fuzzy state space model and the macro-variable proposed in this paper are given by (18), where

$$A = \sum_{i=1}^{m} \mu_i A_i \; B = \sum_{i=1}^{m} \mu_i B_i,\; C = \sum_{i=1}^{m} \mu_i C_i \quad (18)$$

Assuming that each subsystem is controllable, let us assume that the couple *(A, B)* is completely controllable.

Theorem 1: All subsystems of the fuzzy presentation (16), and if we choose the next control u_i

$$u_i = -(C_i^T B_i)^{-1}\left(C_i^T A_i x + \frac{1}{T_c}\Psi_i\right) \quad (19)$$

Then the subsystem is stable.

Proof: Lyapunov candidate function was selected as

$$V_i = \frac{1}{2}\Psi_i^T \Psi_i \quad (20)$$

Therefore

$$\dot{V}_i = \Psi_i^T \dot{\Psi}_i \quad (21)$$

$$= \Psi_i C_i^T (A_i x + B_i u_i) \quad (22)$$

$$= -\frac{1}{T_c}\Psi_i^2 \quad (23)$$

then :

$$\dot{V}_i \leq 0 \quad (24)$$

Based on the second theorem of Lyapunov, stabilization of the subsystem is ensured by the control law (19).

Theorem 2: If we apply the following synergetic control for the global fuzzy system (11),

$$u = -\left(\sum_{i=1}^{m} \mu_i C_i \sum_{i=1}^{m} \mu_i B_i\right)^{-1}\left(\sum_{i=1}^{m} \mu_i C_i \sum_{i=1}^{m} \mu_i A_i\, x + \frac{1}{T_c}\Psi\right) \quad (25)$$

Then the global system is stable.

Proof: Choosing the Lyapunov candidate function to be

$$V = \frac{1}{2}\Psi^T \Psi \quad (26)$$

Therefore

$$\dot{V} = \Psi^T \dot{\Psi} \quad (27)$$

$$= \Psi C^T (Ax + Bu) \quad (28)$$

$$= \Psi\left(\sum_{i=1}^{m} \mu_i C_i \sum_{i=1}^{m} \mu_i A_i\, x + \sum_{i=1}^{m} \mu_i C_i \sum_{i=1}^{m} \mu_i B_i\, u\right) \quad (29)$$

$$= -\frac{1}{T_c}\Psi^2 \quad (30)$$

thus:

$$\dot{V} \leq 0 \quad (31)$$

5. Results of the Simulation

First, the Takagi-Sugeno fuzzy model is employed to describe the single-machine infinite-bus power system. Each subsystem is modeled using four first-order differential equations. The infinite bus is then subjected to a three-phase fault, which lasts for 60 ms before being cleared. The proposed power system stabilizer can be developed using several fuzzy sets for all variable states. The fuzzy sets for $P \in [0.4500,\ 3.5730]$ and $Q \in [-0.2668,\ 1.8143]$ are determined by the membership functions shown in Figure 1 and Figure 2, respectively. The simulation results are presented to demonstrate the robustness and performance of the proposed global fuzzy synergetic approach.

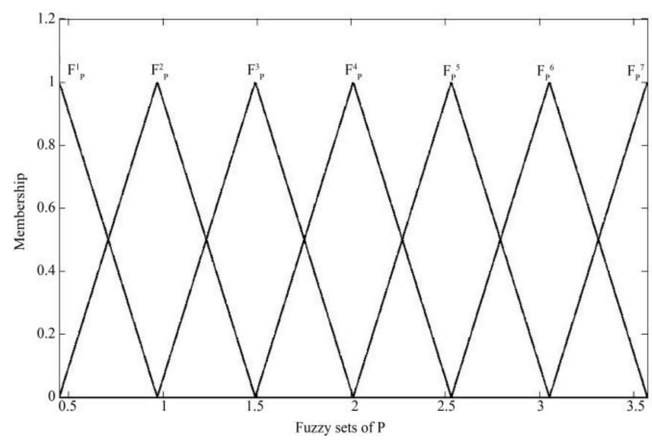

Fig. 1 Active power fuzzy sets

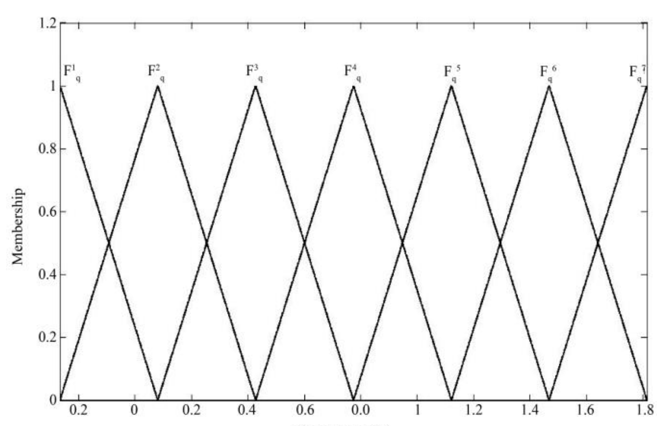

Fig. 2 Reactive power fuzzy sets

In the general case, fuzzy rules are

IF P is F_P^i AND … Q is F_Q^i then

$$\dot{x} = A_i x + B_i u \qquad i = 1,2,\ldots,49 \qquad (32)$$
$$\Psi = C_i^T x$$

therefore

IF P is F_P^1 AND … Q is F_Q^1 then

$$\dot{x} = A_1 x + B_1 u \qquad (33)$$
$$\Psi = C_1^T x$$

IF P is F_P^3 AND … Q is F_Q^7 then

$$\dot{x} = A_{21} x + B_{21} u$$
$$\Psi = C_{21}^T x \qquad (34)$$

IF P is F_P^7 AND … Q is F_Q^7 then

$$\dot{x} = A_{49} x + B_{49} u \qquad (35)$$
$$\Psi = C_{49}^T x$$

Where

$$A_1 = \begin{bmatrix} 0 & -0.1745 & -0.0548 & 0 \\ 377 & 0 & 0 & 0 \\ 0 & -0.2600 & -0.4630 & 0.1667 \\ 0 & -41.6903 & -364.7271 & -20 \end{bmatrix},$$

$$B_1 = [0 \quad 0 \quad 0 \quad 1000]^T,$$

$$C_1 = [-0.8993 \quad 0.2500 \quad 0.0872 \quad 0.0010]^T \qquad (36)$$

$$A_{21} = \begin{bmatrix} 0 & -0.2498 & -0.1117 & 0 \\ 377 & 0 & 0 & 0 \\ 0 & -0.1599 & -0.4630 & 0.1667 \\ 0 & 80.2816 & -571.3554 & -20 \end{bmatrix},$$

$$B_{21} = [0 \quad 0 \quad 0 \quad 1000]^T,$$

$$C_{21} = [1.0831 \quad 0.1832 \quad 0.0872 \quad 0.0010]^T \qquad (37)$$

$$A_{49} = \begin{bmatrix} 0 & -0.2499 & -0.4158 & 0 \\ 377 & 0 & 0 & 0 \\ 0 & -0.2483 & -0.4630 & 0.1667 \\ 0 & 294.2885 & -688.7488 & -20 \end{bmatrix},$$

$$B_{49} = [0 \quad 0 \quad 0 \quad 1000]^T,$$

$$C_{49} = [0.2916 \quad 0.0480 \quad 0.0872 \quad 0.0010]^T \qquad (38)$$

The proposed stabilizer is then compared with a Synergetic Power System Stabilizer (Synergetic PSS) and Lead-Lag PSS (CPSS) in all cases. The conventional stabilizer of the Power System (CPSS) is given in the following Figure 3.

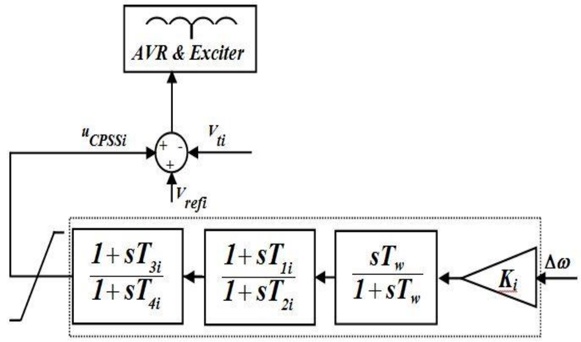

Fig. 3 Conventional IEEE lead-lag power system stabilizer

Where T_w is the constant of the washout time. $T_{1i} - T_{4i}$ are the power system stabilizer time constants, and K_i is the power system stabilizer gain of the generator i. The calculation of the parameters of the conventional power system stabilizer is given in [14] (Table 1).

Table 1. Lead-lag power system stabilizer parameters

	K	T1	T3
CPSS	46.6588	0.4153	0.2698

To prove the effectiveness of the Takagi-Sugeno method, we took three extreme operating points for Single Machine Infinite Bus (SMIB), the first in light load if $P = 1p.u$ and $Q = -0.1933$. Using equations (18), we find

$$A = \begin{bmatrix} 0 & -0.1113 & -0.1316 & 0 \\ 377 & 0 & 0 & 0 \\ 0 & -0.2804 & -0.4630 & 0.1667 \\ 0 & 110.7781 & -395.4493 & -20 \end{bmatrix},$$

$$B = [0 \quad 0 \quad 0 \quad 1000]^T,$$

$$C = [-1.4669 \quad 0.0614 \quad 0.0872 \quad 0.0010]^T \qquad (39)$$

The synergetic parameter $T_s = 0.170$ [14]. The result of a simulation obtained is compared with the Conventional Power System (CPSS) and the Synergetic Power System Stabilizers (Synergetic PSS) (Figure 4).

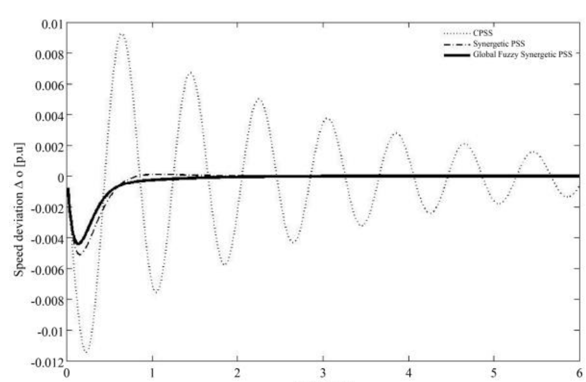

Fig. 4 Speed deviation $\Delta\omega$ for light condition

We do the same work with the case of a normal load, $P = 1.630p.u$ and $Q = 0.0665p.u.$ the system becomes

$$A = \begin{bmatrix} 0 & -0.1060 & -0.2130 & 0 \\ 377 & 0 & 0 & 0 \\ 0 & -0.2783 & -0.4630 & 0.1667 \\ 0 & 196.6139 & -520.5710 & -20 \end{bmatrix},$$

$$B = [0 \quad 0 \quad 0 \quad 1000]^T,$$

$$C = [-0.9714 \quad 0.0352 \quad 0.0872 \quad 0.0010]^T \qquad (40)$$

The simulation result is given in Figure 5 $T_s = 0.0125$. The performance of the proposed method in comparison to both conventional and synergetic power system stabilizers is shown in Figure 5.

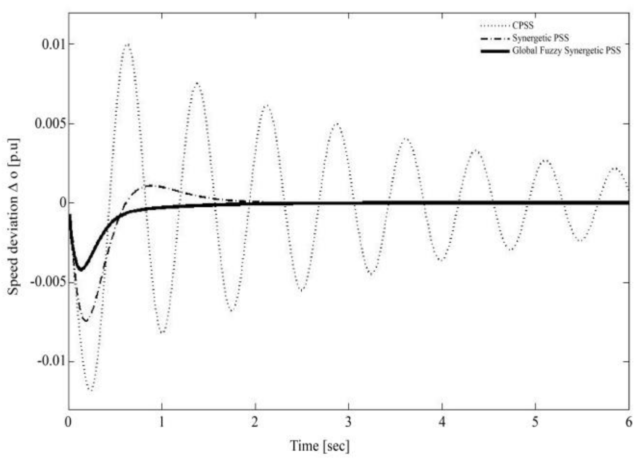

Fig. 5 Speed deviation $\Delta\omega$for nominal condition

The last test for a single machine infinite bus is during a heavy load, where $P = 2.20p.u \quad Q = 0.7127p.u.$ the synergetic vector is $T_s = 0.0100$, the global system is

$$A = \begin{bmatrix} 0 & -0.1530 & -0.2667 & 0 \\ 377 & 0 & 0 & 0 \\ 0 & -0.2578 & -0.4630 & 0.1667 \\ 0 & 213.3299 & -604.1566 & -20 \end{bmatrix},$$

$$B = [0 \quad 0 \quad 0 \quad 1000]^T,$$

$$C = [-0.3701 \quad 0.0439 \quad 0.0872 \quad 0.0010]^T \qquad (41)$$

The simulation result of the proposed control compared with a synergetic control and the conventional control is presented in Figure 6.

In this section, we used Ackerman's method to obtain the synergetic vector and subsystem model in different operating points, and we applied the Takagi-Sugeno method to obtain the global model.

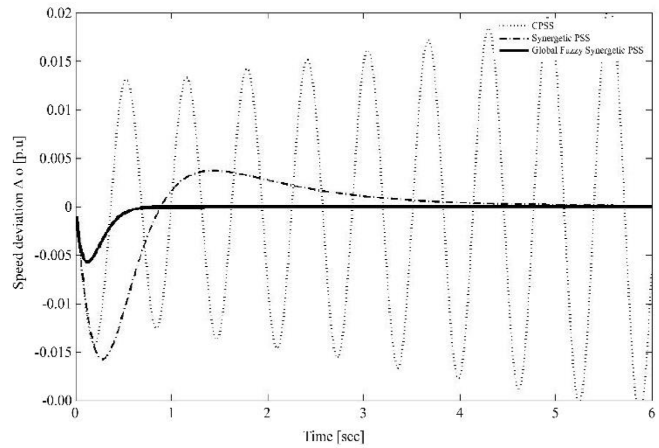

Fig. 6 Speed deviation $\Delta\omega$ for heavy condition

Light and heavy load operations are applied to the power system in order to evaluate the stability of the proposed stabilizer further, illustrating once again precisely how better the proposed controller operates in a single synchronous machine power system than its conventional counterpart.

6. Discussion

Several operating points were considered in this study to demonstrate the effectiveness of the proposed global fuzzy synergetic power system stabilizer in damping oscillations following major disturbances, compared to other stabilizers. The proposed stabilizer helps the generator maintain synchronism during such disturbances.

Three case studies were conducted to evaluate the performance of the fuzzy synergetic stabilizer designed using Ackermann's formula. The results were compared with those obtained using a conventional power system stabilizer and a standard synergetic stabilizer. After the fault is cleared, the system rapidly returns to a stable operating point with the aid of the proposed stabilizer.

7. Conclusion

- Equation We introduced in this study, a global fuzzy synergetic power system stabilizer based on Ackermann's formula that improves your effectiveness to damp oscillations and thus enhances the transient dynamics of synchronous machine power systems.
- Three case operating conditions, as well as several perturbations, were used for the evaluation of the proposed global fuzzy synergetic power system stabilizer, which is robust and quickly reduces oscillations that, if not treated, could result in synchronism loss.
- Simulation results prove superior performance over the lead-lag power system stabilizer, synergetic power system stabilizer, and satisfactory transient behavior, showing better performance.
- Stability is proved by the second theorem of Lyapunov.

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